Final Progress Report

on

"Aeromechanics of an Optimized, Actively-Morphing Rotor System"

to

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Program Manager: Dr. Judah Milgram (judah.milgram@navy.mil)

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"Aeromechanics of an Optimized, Actively-Morphing Rotor System"

Final Report

Period covered: FY09 – FY12

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1. Overview

The objective of this research was to investigate the potential of rotor morphing to improve the performance of baseline helicopter configurations. The morphing parameters that have been considered in this report are variable rotor speed and variable rotor radius. Both of these parameters are considered in steady state only, so that transients that would be introduced during blade morphing are not considered. Additional morphing concepts including variable twist, chord, camber and tip shape could not be completed due to time constraints.

The comprehensive rotorcraft analysis code, UMARC, was modified to accommodate steady variations. The structural model is a full, non-linear, finite element analysis formulation. Each blade is modeled as an articulated, flexible beam with coincident flap and lag hinges. The aerodynamic model is a Weissinger-L type lifting-surface model coupled with 2D airfoil tables, unsteady effects are captured using the Leishman-Beddoes model, and a time accurate free wake model, captures the wake.

2. Baseline rotor description

The baseline helicopter selected for this study is the UH-60A Black Hawk helicopter. This helicopter has been extensively studied including both flight and wind tunnel tests as well as a good description of the rotor geometry. UMARC has been validated against this data and shown to be capable of predicting flight trim characteristics and performance well, and giving a good indication of the trends of the oscillatory loads transferred to hub that cause vibration. The important rotor characteristics are described in Table 1.

Table 1: Black-Hawk baseline properties.

Properties	Value
Type	Articulated

Number of blades	4
Radius	25 ft
Twist	-16^{o} (linear)
Rotor speed	260 RPM
Solidity	0.082

It is important to realize that the Black-Hawk helicopter has been designed with compromises that allow it to perform its flight envelope without any morphing characteristics. The potential of a morphing rotor is that some of these compromises can be removed or reduced, which could result is a different helicopter with superior performance than is possible by retrofitting morphing characteristics to the current rotor. The goal of this study is to investigate that performance margins available which can allow greater flexibility in the design of the next generation helicopters.

3. Variable rotor speed

Summary

The results of the study showed that there is the potential for improving helicopter performance through variation in rotor speed alone. The degree of improvement is very much dependent on the operating weight (disk loading) and desired flight speed of the mission, and no single valued reduction in rotor RPM is always suitable. For example, at a mission weight of 18,400 lbs., a maximum power reduction of 10% can be achieved at moderate cruise speeds. At 14,000 lbs, which corresponds to the empty weight of the Black-Hawk, up to 20% power reduction is achievable. This condition can only be realized with some form of lift compounding, which cab be realistic for high speed helicopters.

The effect of rotor speed variation on the hubloads transferred to the fixed frame is investigated next. It is found that in general the vertical shear forces are reduced at all flight speeds by reducing the rotor speed. The in-plane shear force and the in-plane moments however are increased over the baseline. However this increase is small, and less than the peak loads expected during normal flight of the baseline until higher flight speeds are attained. Dynamic stall is identified as driving up the hubloads dramatically for the lowest rotor speeds considered.

Important Results

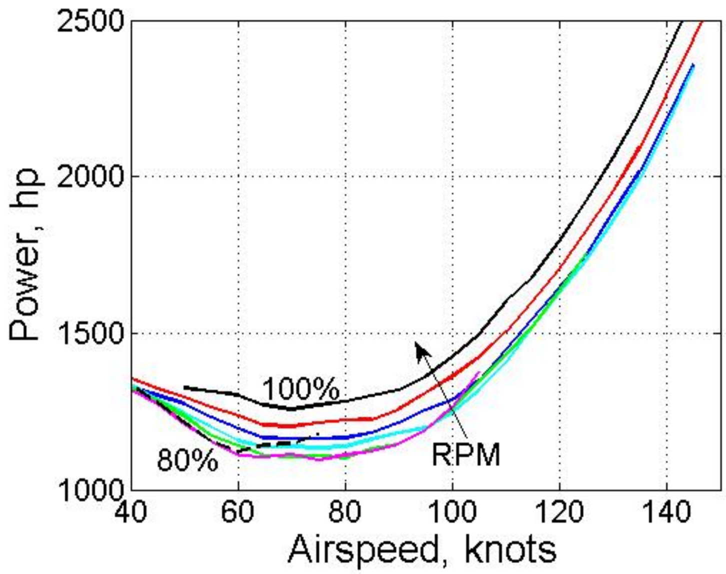

Figure 1: Power variation with rotor speed (W=18,400 lb).

Performance

Figure 1 shows the variation of main shaft power with varying rotor speeds for a sweep of airspeeds between 40 and 150 knots. Rotor speeds between 80% and 100% of nominal (27 rad/s) are considered. It was found that increasing the rotor speed above 100% did not offer any benefits for power required or hubloads and the lowest rotor speed considered was determined by the rotor speed at which no further reduction in power could be achieved across the flight envelope. It is clear that the greatest benefits are possible in the power bucket with diminishing reductions in power as the airspeed is increased. In addition the result shows that for a reduced RPM, the maximum airspeed that can be reached before the rotor cannot supply sufficient thrust to maintain trim is reduced. A similar study for two additional helicopter gross weights is shown in Figure 2. In this result the width of each power band represents the scope for power reduction available for each disk loading. The lowest weight case, 14,000 lb, could achieve a peak power reduction of 20% after reducing the rotor speed to 72% of baseline whereas the 21,000 lb case could achieve no more than 5% power reduction. This result shows the dependence of rotor speed reduction on disk loading and highlights that the greatest efficiency for variable speed concepts would be achieved for either low disk-loading rotors, or, when the rotor is off-loading in forward flight by some additional lift compounding.

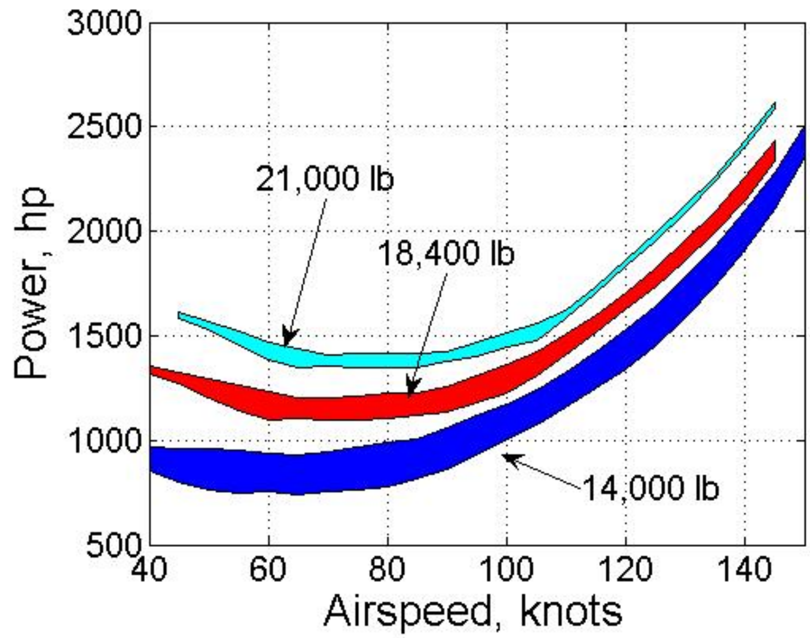

Figure 2: Bands of power reduction available through rotor speed reduction for three gross weights.

To investigate the aerodynamic environment for the slowed rotor, Figure 3 shows the local distribution of angle of attack seen by the airfoil for rotor speeds varying between 100% and 80% of baseline at 80 knots. There is a clear increase in the average angles seen by the rotor disk as the rotor speed is decreased. This occurs because the dynamic pressures are reduced requiring increased pitch angles to achieve the same lift. This allows the airfoils to operate more efficiently as is shown in Figure 4 that plots the angle of attack at several radial stations against the local maximum airfoil $C_L^{3/2}/C_D$, which is an indication of airfoil efficiency. Subplots 4(c)-4(f) show that at 80% rotor speed, the airfoil operates more efficiently than the baseline. However on the retreating side of the rotor, the angle of attack is increased well above static stall limits shown in the dark regions of subplot (f) in Figure 3 and (a) and (b) of Figure 4. This loss in efficiency drives up the power required and limits the thrust that the rotor can produce. The regions of the rotor disk that exceed the stall limits of the airfoil are highlighted in Figure 5.

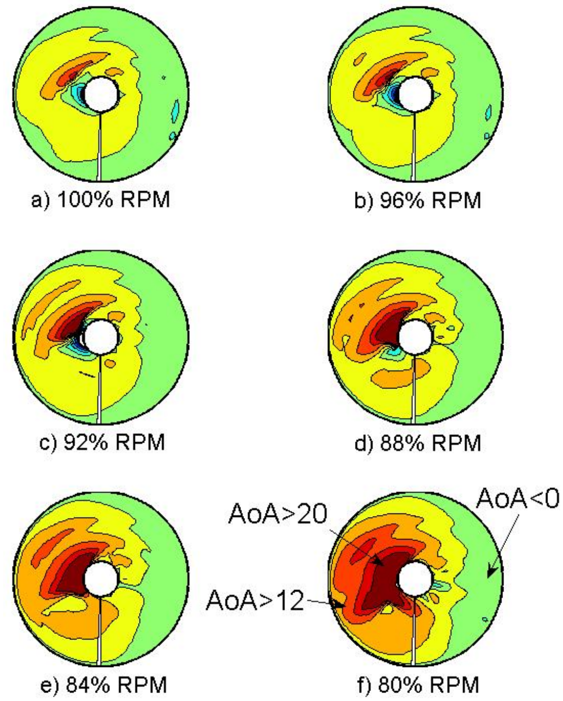

Figure 3: Angle of attack distribution with variation in rotor speed at 80 knots. (W = 18,400 lb)

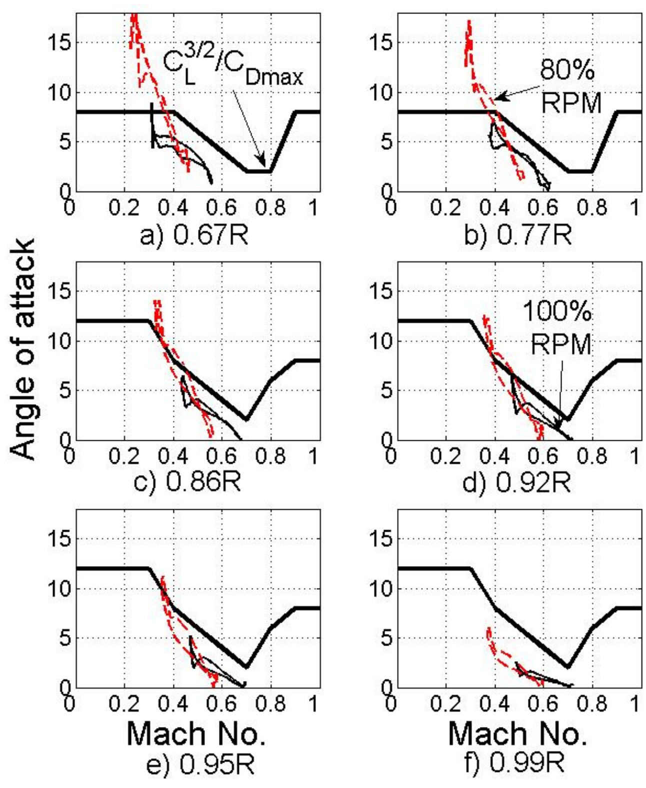

Figure 4: Airfoil efficiency with variable rotor speed at 80 knots. (W = 18,400 lb)

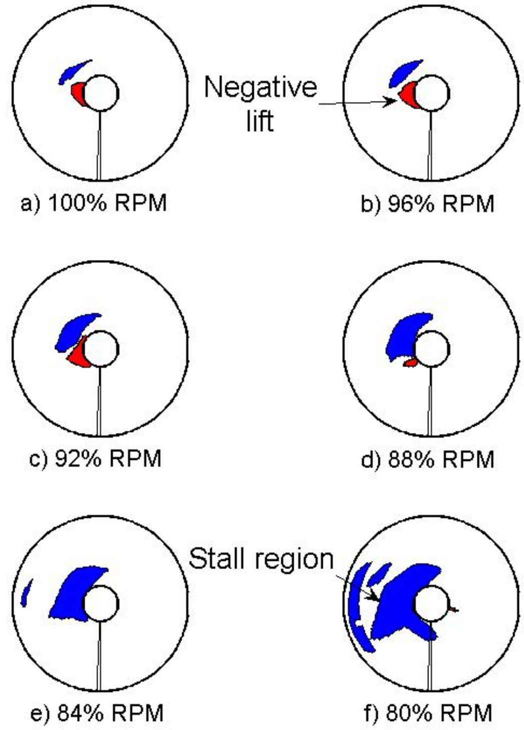

Figure 5: Stall distribution with rotor speed variation at 80 knots. (W = 18,400 lb)

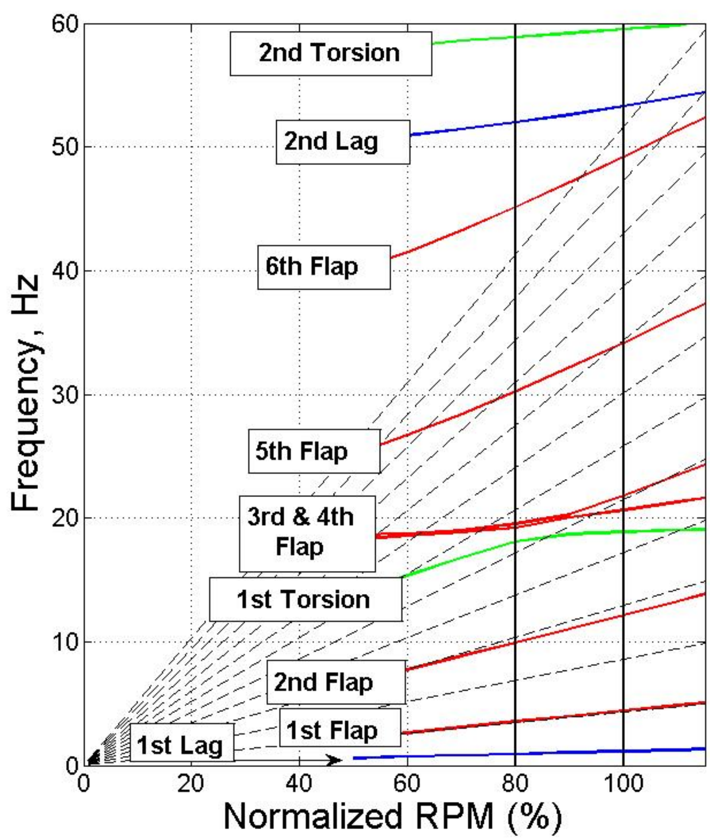

Figure 6: Fan plot showing first 10 rotor frequencies.

Hubloads

Varying the rotor speed has implications for the rotor frequencies and may cause particular structural modes to be excited by the aerodynamic forcing. The fan plot of the rotor was considered and is shown in Figure 6. It is clear that there is potential of interactions in the 1st torsion and the 3rd/4th flap modes with the 5/rev forcing. However these were not encountered in these studies. In general however a rotor should be tailored to avoid these resonant frequencies, or otherwise a rotor speed schedule can be designed to minimize time near these frequencies.

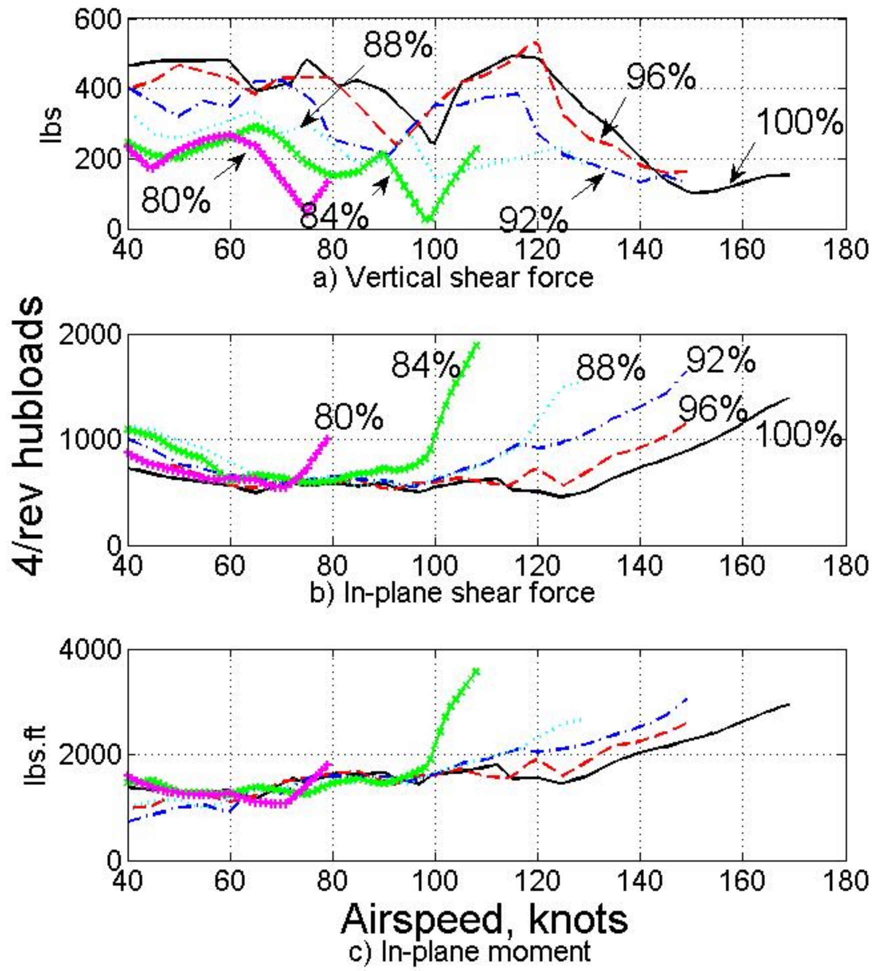

Figure 7: 4/rev hubloads with variation in hubloads. (W = 18,400 lb)

Figure 7 shows the variation in magnitude of the 4/rev harmonic of the rotor loads in the fixed frame with reducing rotor speed. The conclusions are mixed, showing that while the vertical shear force may be reduced with reducing rotor speed, the in-plane shear force and moment are generally increased. The in-plane shears show that as airspeed increases operating at a rotor speed for reduced power will cause increased vibratory loads. This has implications for the structural limitations of the rotor, fatigue, as well as for pilot comfort.

In general the rate of increase of the magnitude of the loads is slow and does not exceed the maximum experienced by the baseline rotor until reaching high-speed flight. At lower speeds the increase is only small. However the 80% and 84% rotor speed cases show divergent behavior. This behavior is investigated further in Figure 8, which plots the pitching moment coefficient about the azimuth for a rotor operating at 84% of baseline with increasing airspeed form 60-110 knots. The step changes in pitching moment occurring at 270^{o} azimuth for airspeeds above 100 knots indicate dynamic stall. This event, present in the 80% case as well, would appear to contribute towards the sudden increase in the hubloads shown at 90 knots for this rotor speed.

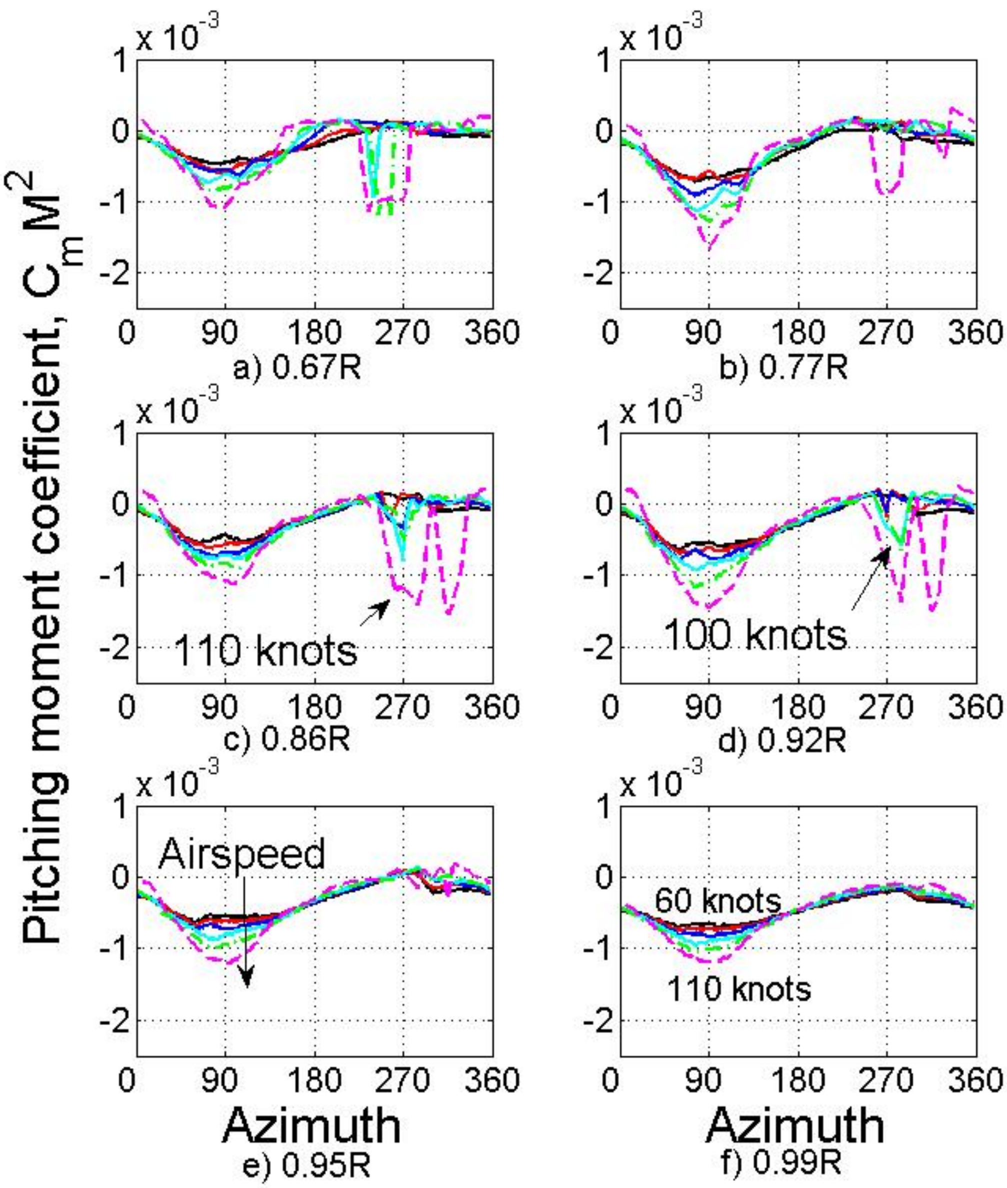

Figure 8: Pitching moment coefficient at 84% RPM for increasing airspeed. (W = 18,400 lb)

4. **Variable Rotor Radius**

Summary

Helicopter performance change with radius variation at different thrust levels is investigated. Two mechanisms for radius variation are considered. The first considers a telescoping blade area so that the lifting area varies with radius. The second considers radius change for a constant lifting rotor but with a varying root cut out.

The results show that helicopter power can be reduced most significantly at high speeds for low required thrusts. As the required rotor thrust is increased, the power reduction decreases at low speeds and rotor power becomes larger than the baseline at higher speeds. For a 16,000 lbs helicopter up to 180 HP reduction can be achieved at 170 knots by a 5% reduction in radius. This corresponds to about a 5% reduction in total power.

Vehicle trim controls are shown to increase with reducing radius corresponding to the reduced dynamic pressures at the tip requiring increased pitch angles to produce the required lift. Also, the roll and pitch angles decrease with decreasing radius.

Finally, the variation in fixed frame loads is investigated with radius variation. The vertical shear 4/rev loads are shown to decrease by as much as 50% with radius for much of the flight envelope. At high speeds, the magnitudes become larger than the baseline, although not to alarming levels. The in-plane 4/rev loads are largely unchanged for low to moderate speeds, but exhibit the same rise in loads at high speeds; however, the onset begins at progressively earlier speeds as radius is educed further. At high speeds they may be significantly higher than baseline. The in-plane moments are reduced by as much as 50% at low speeds and show similar magnitudes to the baseline rotor at moderate to high speeds.

Important results

Performance

Figure 9 shows the variation in rotor power for step changes in rotor radius at 16,000 lbs thrust. Note that the parasitic contribution to power has been removed since it is nearly invariant with radius for a given airspeed (only a small dependency on vehicle trim). At lower speeds, radius reduction shows only marginal benefit, or increases power required for the 86% radius case. This is in agreement with the momentum theory result that shows that the minimum power in hover, for a fixed tip speed, requires maximizing radius. As the airspeed is increased, reducing the radius decreases the rotor power. For this thrust condition, a reduction in radius to 90% of nominal gives the greatest power benefit at moderate to high speeds but then exhibits a steep rise in power at higher speeds eventually exceeding that of the baseline rotor. An 86% radius reduction was the smallest radius that showed any benefit but only over a narrow range of airspeeds around 90 knots, before growing higher than the baseline. The 96% radius condition

shows almost constant power reduction from 100 knots to 170 knots with no indication at 170 knots that the rotor is approaching stall.

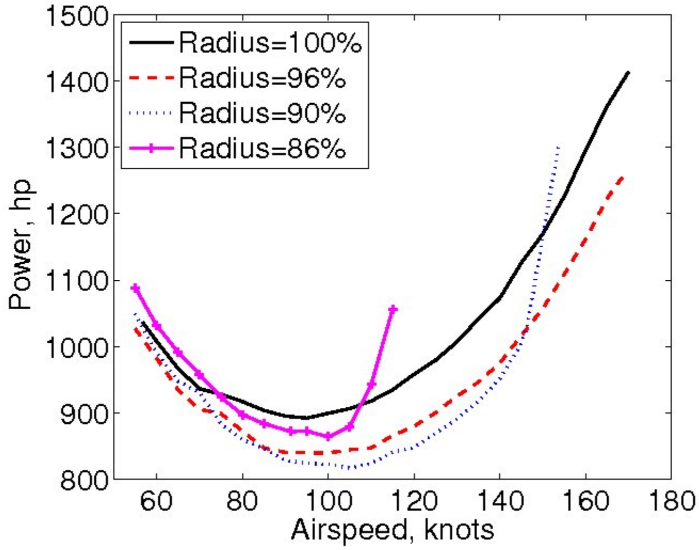

Figure 9: Power variation with rotor radius - Parasitic power removed (W=16,000 lbs)

The two components contributing to the total power are the induced and profile power as shown in Figure 10 and Figure 11 respectfully. The induced power increases as the radius is reduced since induced power is an inverse function of the disc area.. The profile power shown in Figure 11 displays the dominating effect on the total power of radius reduction. As the radius reduces, for a constant rotor speed, the profile power reduces approximately with Radius^4 before being impacted by stall. As the airspeed increases, the contribution to the total power from induced power reduces while that from profile power increases. Thus radius reduction is more effective to the performance improvement at moderate to high speeds.

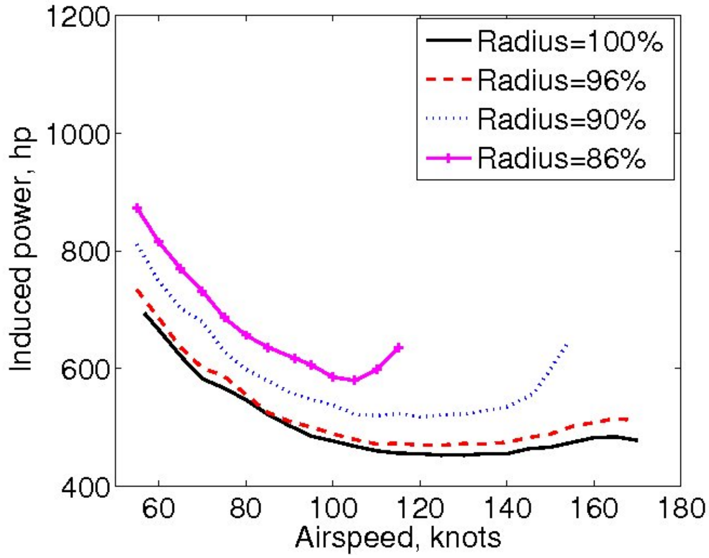

Figure 10: Induced power variation with rotor radius. (W=16,000 lbs)

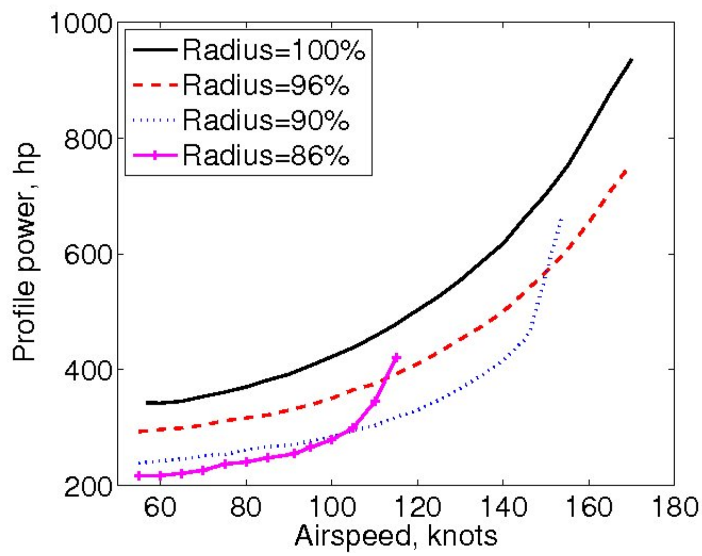

Figure 11: Profile power variation with rotor radius. (W=16,000 lbs)

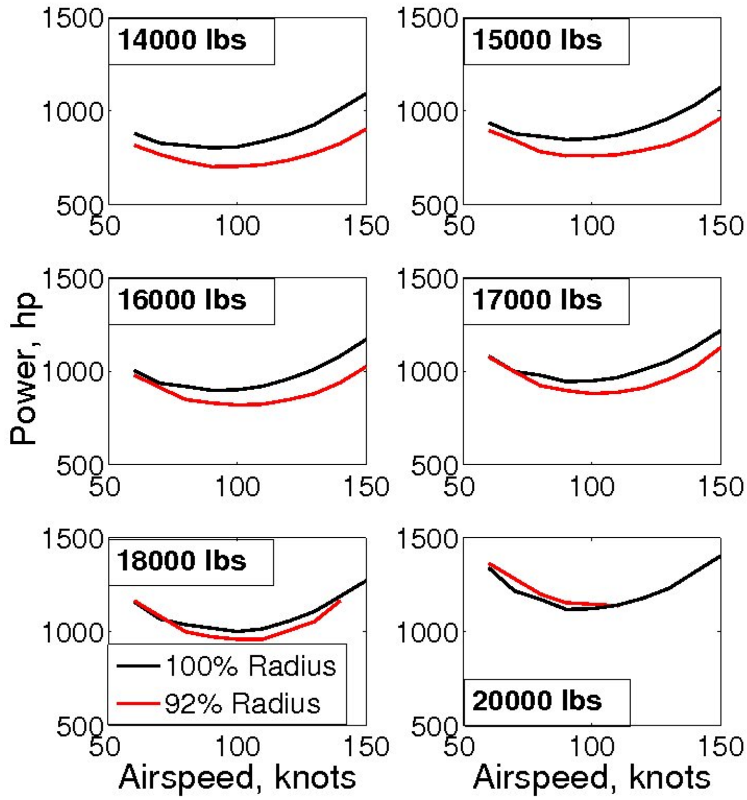

Figure 12: Influence of helicopter thrust on total power at 92% radius.

The impact of helicopter thrust on the performance with radius reduction is shown in Figure 12 by varying the thrust between 14,000 lbs and 20,000 lbs. Here only two cases of 100% and 92% radius are considered. For the lowest thrust case, the 92% radius shows overall benefits for the speed range considered and the trend indicates that increasing power reduction will be achieved at higher speeds. This condition is only realistic when some lift compounding is used in conjunction with variable radius to off-load the rotor. As the thrust increases, the low speed performance improvements are lost by 17,000 lbs as well as some indication of stall at high speeds (150 knots) by the more rapid increase in the power slope about 140 knots. At 20,000 lbs., decreasing the radius to 92% only acts to increase the power required.

The vehicle trim controls are shown in Figure 13. The collectives and cyclics are each increased for a given flight speed as the radius is reduced. This corresponds to more lift being produced over a smaller disc area requiring larger pitch angles. The trimmed shaft pitch and roll angles are decreasing with reduced radius as smaller rolling and pitching moments are generation by the smaller rotor due to the reduced moment arm.

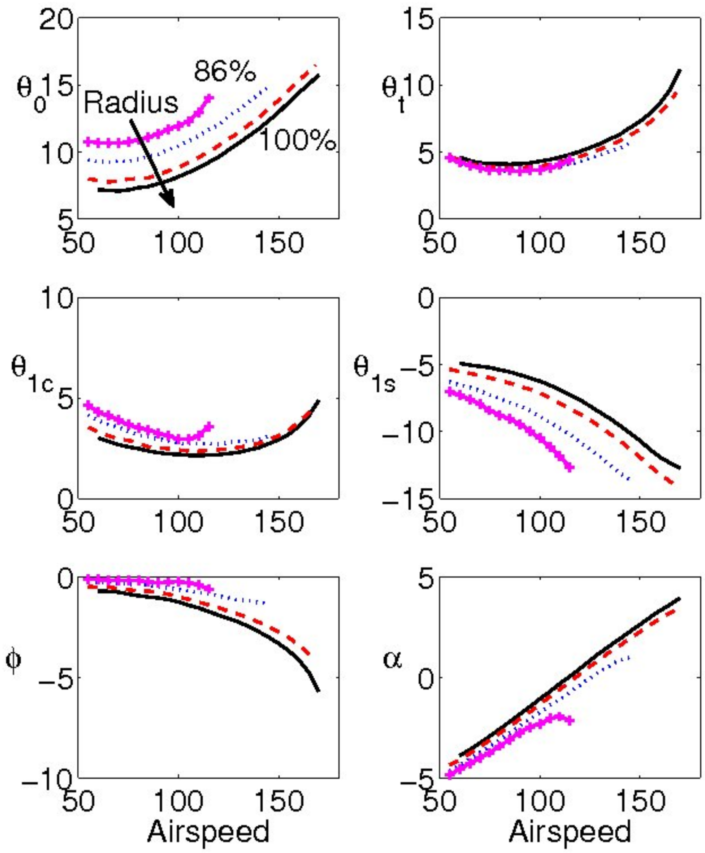

Figure 13: Variation of vehicle trim with reduced radius. (W-16,000 lbs)

Radius variation concepts

Two broad concepts to vary radius were considered as shown in Figure 14 and Figure 15. The first concept achieves radius variation by moving a constant blade area inboard and outboard along the spar. This results in a constant lifting area, but the maximum radius reduction is limited to the extent of the root cut out. Physically some part of the cut out is required for blade cuff, flap hinges and pitch link attachments. A practical application would have to incorporate a larger root cut out than otherwise desired to allow a reasonable degree of radius variation.

The second radius variation concept changes the radius by telescoping part of the blade into another. This can be done in two or more sections. Radius reduction in this way does not affect the root cut out; however, the blade lifting area is reduced by radius variation. This concept also has implications for blade twist since only a linear twist can be implemented over the overlapping regions. The mechanics of such a construction are challenging to minimize friction between the overlapping blades, while maintaining aerodynamic surfaces.

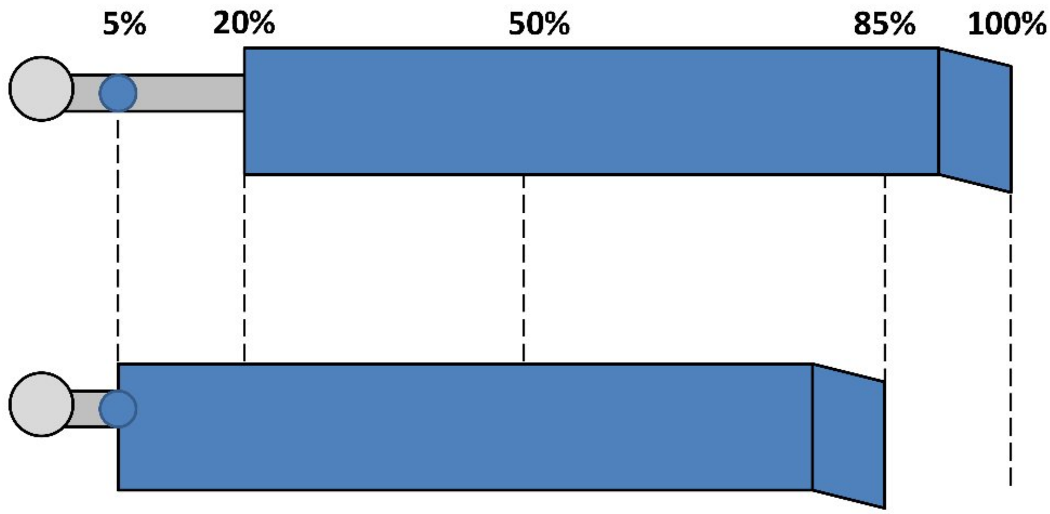

Figure 14: Radius variation through variable root cut out.

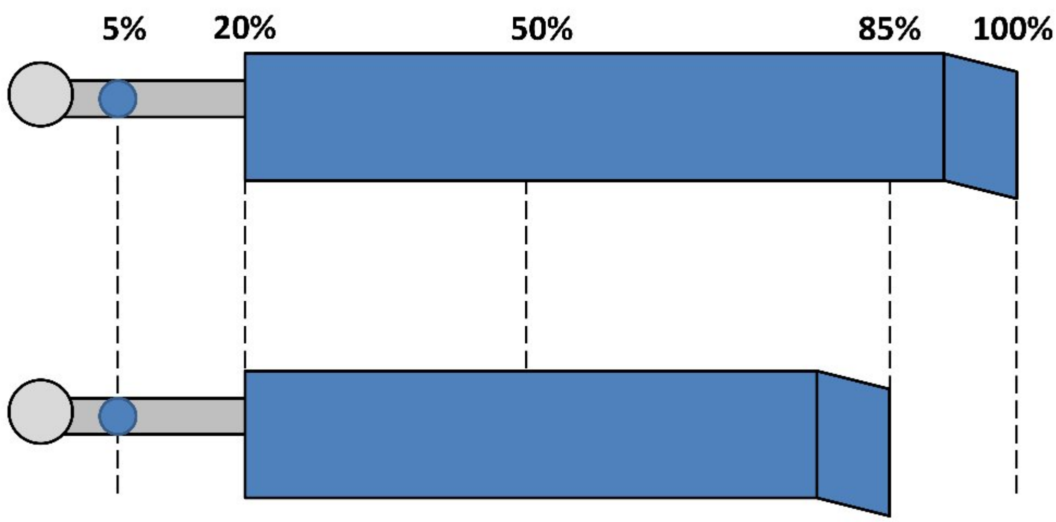

Figure 15: Radius variation by telescoping blade.

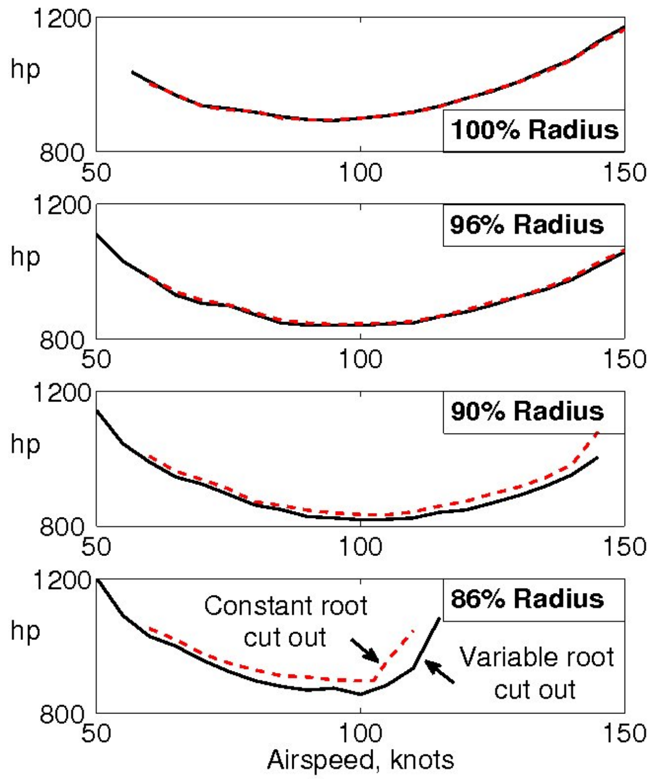

Figure 16: Comparisons of performance of radius reduction concepts.

Figure 16 compares the performance of the two radius variation concepts for a given thrust required. At 100% radius extension there is no difference as expected. At 86% radius the variable root cut out concept offers a small improvement in performance as the speed is increased. This indicates that the additional lift generated by the blade in the root cut out region offers a benefit. However, at increased advance ratios, where the reverse flow aerodynamics become more important, the download generated in the reverse flow region will possibly have a strong negative impact.

Mission analysis

The practical applications of the power reduction from radius reduction have been considered in terms of equivalent velocity in Figure 17 and additional payload in Figure 18. The additional velocity result is determined by comparing the airspeed for the same total power between the baseline and the reduced radius cases. For a 16,000 lbs helicopter, between 4 and 6 knots of additional speed can be achieved for the same power across the normal power band in high speed flight. This has a direct implication for mission productivity. The second result in Figure 18 looks at the fueled savings for a 92% radius case compared to the baseline as a function of payload. This result is the implication of the results shown in Figure 12 that the benefits of radius reduction decrease rapidly as thrust increases and at 6,000 lbs payload (20,000 lbs

vehicle thrust) there is no advantage to be gained. More conservative mission profiles for gross weights between 16,000 lbs and 18,000 lbs can save between 20 and 40 lbs/hr.

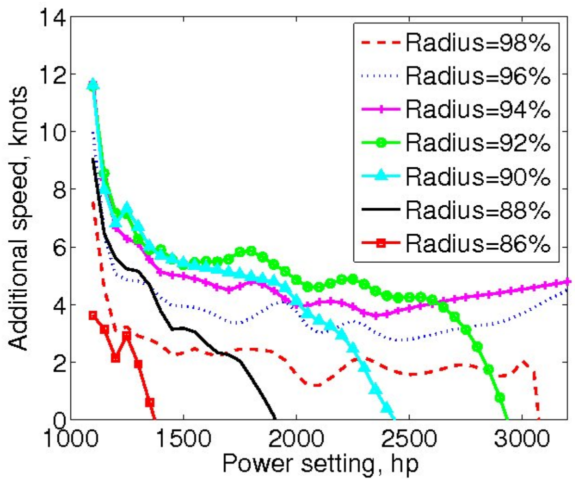

Figure 17: Additional airspeed available from radius variation. (W=16,000 lbs)

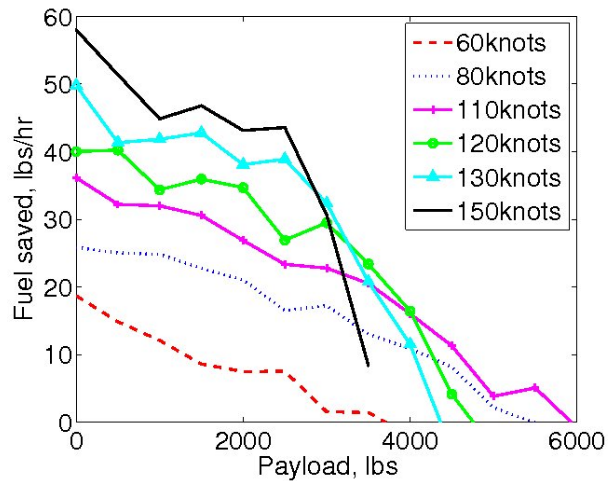

Figure 18: Fuel savings available from radius variation (W_{empty}=14,000 lbs)

Another important consideration for a rotary wing vehicle performance is autorotative ability. Figure 19 shows the variation of rotor autorotative index (AI) as a function of disc loading (DL). The autorotative index is a measure of the helicopters ability to land safely if power is lost to the rotor while in flight where a larger number means that the rotor has more stored energy available to land safely. Although this researcher is unaware of the autorotative index value that ensures a safe landing, comparison to the baseline rotor, which is shown between 14,000 lbs and 20,000 lbs provides some indication of the safety trade off with radius reduction (assuming constant RPM). Radius reduction progressively reduces the A.I. so that at 86% radius, the vehicle would be unsafe to land regardless of payload. Control schemes to extend the radius again after engine failure would need to be very robust to counteract this.

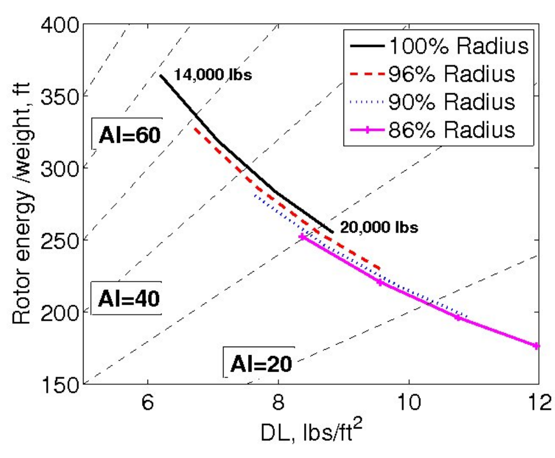

Figure 19: Autorotative index as a function of radius.

Variable radius aerodynamics

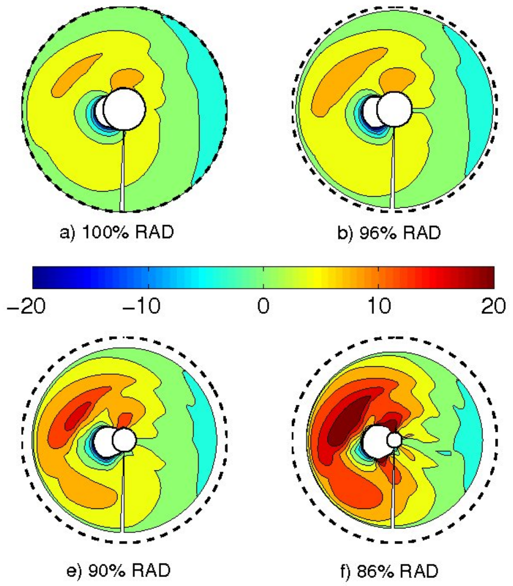

Figure 20: Angle of attack distribution with radius reduction (W-16,000 lbs & 115 knots)

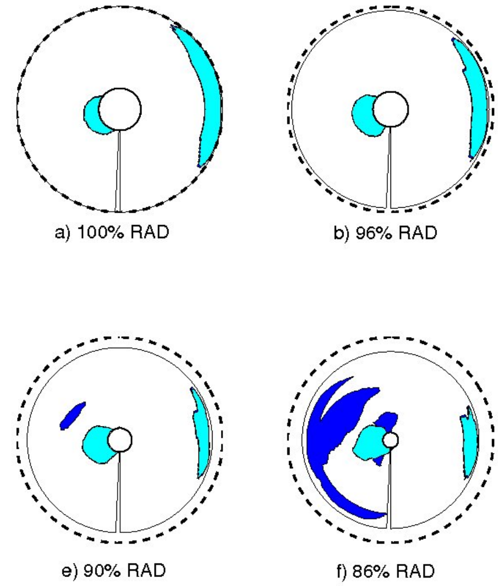

Figure 21:: Stall (Dark) and negative lift (light) distribution with radius reduction (W-16,000 lbs & 115 knots)

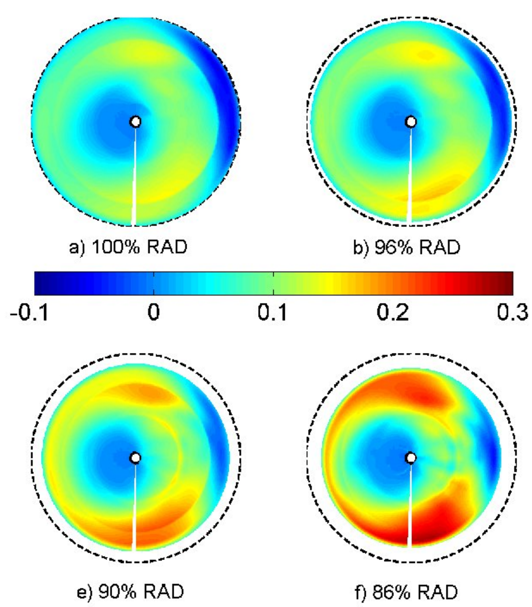

Figure 22: Lift distribution with radius reduction. (W-16,000 lbs & 115 knots)

Figure 20 shows the angle of attack (AoA) distribution for a trimmed 16,000 lbs helicopter at 115 knots, while Figure 21 shows the approximate regions of stall (dark blue), and negative lift generation (light blue). The bottom of the disks corresponds to 0^o azimuth. As the radius is decreases, the AoA must increase to produce the required thrust on a smaller disk area. This predominantly affects the retreating side due to interplay with the blade twist. As the radius is reduced, the effective blade twist reduces at the tip (assuming linear twist) which results in less negative loading on the advancing tip and a net increase in the roll moment produced on the advancing rotor. To counteract this, a larger longitudinal cyclic is required to maintain trim in roll, resulting in higher angles on the retreating side. This combination ultimately leads to blade stall on the retreating rotor, as evident for the 86% case, and leads to the large power increase seen in Figure 9. The normal force distribution is shown in Figure 22 and indicates that as the radius is reduced, more lift in supported by the fore and aft regions of the rotor disk. This is similar to the distribution seen when increasing the advance ratio for a constant radius rotor.

Hubloads

The impact of radius variation on the fixed frame loads is shown in the plots of the 4/rev vertical shear, in-plane shear and in-plane moments in Figure 23, Figure 24 and Figure 25. The vertical shear loads are significantly reduced from the baseline for all low to moderately high speeds for all radius reductions considered. At high speeds (>150 knots) the 4/rev loads climb higher than the baseline but not above levels predicted at lower air speeds. The 86% radius case shows reductions of over 50% with the largest reductions at 90 knots. The in-plane loads show little sensitivity to radius reduction for low to moderate airspeeds. The trend shown by the baseline rotor of rapidly growing magnitudes above 120 knots is followed for the reduced radius rotors but occurring at progressively earlier airspeeds. The 86% radius case shows increasing loads at 100 knots. The in-plane moments of the reduced radius rotors are all reduced from the baseline for low to moderate airspeeds, but follow the trend and magnitude of the baseline at higher speeds.

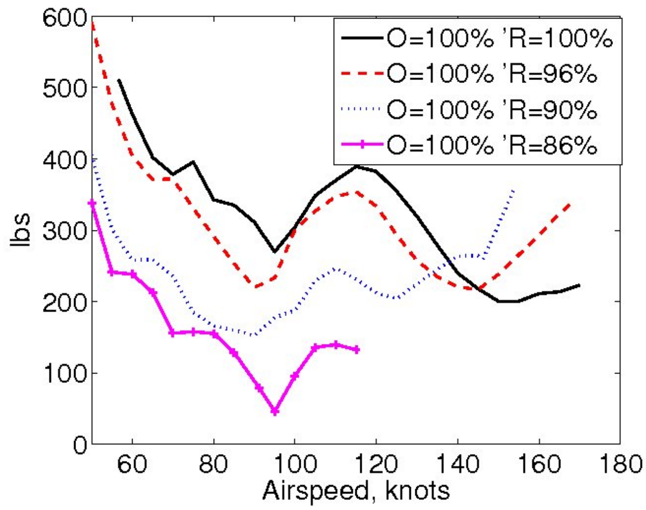

Figure 23: 4/rev vertical shear hubloads variation with radius reduction. (W-16,000 lbs)

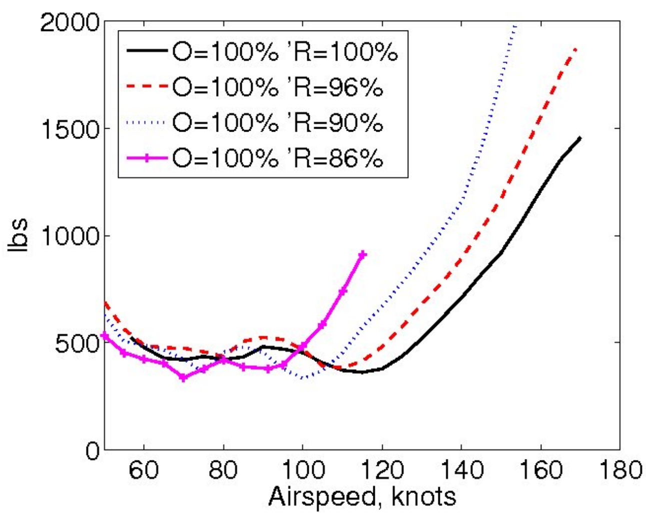

Figure 24: 4/rev in-plane shear hubloads variation with radius reduction. (W-16,000 lbs)

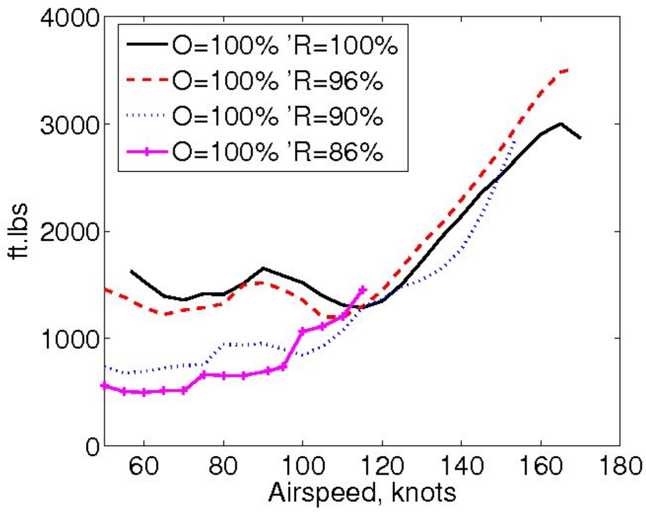

Figure 25: 4/rev in-plane moments hubloads variation with radius reduction. (W-16,000 lbs)

These results indicate that at low speeds vibrations can be reduced where there is limited power reduction, or even a cost to performance from radius reduction. At moderate airspeeds (<100 knots) there is scope for simultaneous vibration reduction and power reduction through any degree of radius reduction, and at high speeds, larger power reductions may be accompanied by an increase in vibrations over the baseline.

5. Conclusions

The two morphing rotor parameters investigated in this research are variable rotor speed and variable rotor radius. Both concepts are shown to give performance benefits to a conventional helicopter in the normal flight envelope (< 170 knots), but the benefits depend on the rotor thrust level and air speed.

For a UH-60 like rotor generating 14,000 lbs of thrust at sea level (equivalent to the vehicle empty weight), rotor speed variation can reduce the shaft power across the entire flight envelope with a maximum reduction of 20% near 80 knots airspeed with the reduction of the rotor speed to 72%. At 21,000 lbs, a peak power reduction of 5% is available in cruise, but this vanishes at moderate to high speeds. Reducing rotor speed allows the rotor to operate at a more efficient condition by maximizing the airfoil lift to drag characteristics, as a function of the rotor thrust. This trades excess stall margin available in some flight conditions for performance. If the rotor speed is reduced excessively, stall on the retreating side increases the power rapidly so that it becomes larger than the baseline, or the rotor is no longer able to generate the required thrust for trim.

The 4/rev vertical hubloads are generally reduced at all airspeeds by reducing rotor speed. The in-plane loads are higher than baseline at low speeds and show little variation from the baseline

in the speed bucket (60-90 knots) unless the rotor starts to stall. At moderately high speeds, the in-plane loads become larger than the baseline as the rotor speed is reduced. The 4/rev in-plane hub moments remain the same order of magnitude with reducing radius at speeds below 100 knots provided the rotor does not stall. For high speeds, the 4/rev loads follow the baseline trend but at increasing magnitudes.

The variable radius results showed the largest performance improvements at high speeds and for lower thrusts. At hover, the power maybe larger than the baseline when the radius is reduced (for a constant rotor speed). The motivation for radius reduction is to decrease power associated with airfoil drag; however, to maintain the same thrust over a smaller rotor the induced inflow must increase causing increased induced power losses. As airspeed increases, the induced power contribution decreases allowing the benefits from profile power reduction to dominate. This behavior is limited by the onset of stall, which drives up the rotor power.

Two broad radius variation concepts were considered. These are constant blade area, where the root cut out changes to accommodate radius change, and a variable blade area concept where a telescoping mechanism changes the blade radius. The differences, in the range of speeds and thrusts considered, are small but grow as the radius is reduced more significantly (86%). The concept with a constant blade area performs better at increased speeds as the contribution from the additional lifting surface in the root cut out grows. This may not be true for very high advance ratios where the download on the retreating side would be detrimental to lift.

The 4/rev vertical shear load can be reduced by over 50% at low to moderate speeds by reducing the radius. At very high speeds, the magnitudes grow larger than the baseline, but remain less than the limits experienced by the baseline rotor at all airspeeds. The in-plane shear loads are unchanged at low speeds, but grow to much larger magnitudes at moderate to high speeds as the radius is reduced. Finally the in-plane moments are significantly reduced (>50%) at low speeds and have similar magnitudes to the baseline at high speeds.

6. Plans and upcoming events

This is a final report.

7. Publications

Bowen-Davies, G., Chopra, I., "Aeromechanics of a variable speed rotor", American Helicopter Society 67th annual forum proceedings, Virginia Beach, VA, May 2-5 2011.

Bowen-Davies, G., Chopra, I., "Aeromechanics of a variable radius rotor", American Helicopter Society 68th annual forum proceedings, Fort Worth, TX, May 1-3 2011.

Awards:

Vertical Flight Foundation (VFF) award received in the master's research category 2011.